2.5 MW PEM Fuel Cell System for Navy Ship Service Power

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In 1997, the Office of Naval Research (ONR) initiated an advanced development program to demonstrate a ship service fuel cell power generation module. The ship service generator supplies the electrical power requirements of the ship. When completed, this program will provide the basis for new fuel cell-based ship service power system designs that will be a viable and attractive option for future U.S. Navy surface ships.

A ship service fuel cell (SSFC) power generation module possesses attractive characteristics for U.S. Navy and other marine vessels. Chief among them is a high system level efficiency that is achieved through the direct electrochemical conversion of fuel. The low acoustic and thermal signatures expected from these systems are also attractive benefits. Simplicity of design adds some additional benefit. Maintenance costs are expected to be low. The fuel cells and stacks themselves have no moving parts and require little or no maintenance. The system "balance-of-plant" which manages fuel, air, and exhaust has few moving parts and contributes to reduced maintenance resulting in cost savings to the Navy and enhanced ship effectiveness. Reduction of power system emissions has become an issue in many harbors throughout the world. Emissions of NOx, CO, and unburned hydrocarbon pollutants from the SSFC generator are reduced up to 95% compared to gas turbines or diesel engines. Finally, fuel cells are inherently modular and can be distributed throughout the ship in a configuration compatible with all-electric ship concepts, and enhanced survivability designs.

The ONR advanced development program currently consists of two phases. During Phase 1, competitive conceptual designs of 2.5 MW SSFC power plants are being prepared, along with critical component demonstrations designed to reduce development risk. The critical demonstrations include testing fuel cell cathode tolerance to salt laden air, military shock and vibration tests of cell hardware, and demonstration of reforming and fuel desulfurization technology using Navy logistic fuel. Phase 1 will be completed in 1999. Phase 2 of the development program, scheduled for completion in 2002, will result in a nominal 500 kW fuel cell ship service generator demonstration module to be constructed and tested in a laboratory setting.

This paper summarizes some of the Phase 1 efforts of a team consisting of McDermott Technology Inc., BWX Technologies, Ballard Power Systems, and Gibbs & Cox. Conceptual design and critical component testing activities are described for a 2.5 MW Proton Exchange Membrane (PEM) SSFC system.

The 2.5 MW SSFC system conceptual design criteria were as follows:

- provide 2.5 MW net electrical power at 450 VAC, 3 phase, 60 Hz;
- run on naval distillate fuel (NATO F-76);
- achieve minimum system level efficiency of 40% (based on lower heating value) at 50% of rated load;
- achieve system size and weight goals of 57 l/kW and 18 kg/kW, respectively;

- achieve estimated cost in production of $1500/kW;
- be developed using commercial or near-commercial technologies;
- be highly reliable and maintainable; and
- be self-contained with respect to water balance and energy balance.

These criteria were addressed through a conceptual design process consisting of trade-off studies, control system development, system layout, and other system level evaluations.

The baseline system concept is shown schematically in Figure 1. This system concept uses an autothermal reformer (ATR) based conceptually on a Defense Advanced Research Projects Agency (DARPA) and U.S. Army Research Office-funded, logistic fueled, adiabatic reformer designed and built by International Fuel Cells[1]. Downstream of the ATR is a series of components that clean up the reformate gas (remove CO and H_2S) before the hydrogen rich gas is sent to the fuel cell. The sulfur cleanup is accomplished by use of a set of cycling regenerable sorbent beds followed by a polishing sulfur sorbent bed. This desulfurization system is able to achieve 1 ppm of sulfur in the reformate gas. The CO is removed by water-gas shift in high and low temperature shift reactors followed by selective oxidation of CO over a precious metal catalyst. The spent fuel and air from the fuel cell are mixed and burned to drive a turbocompressor and recover compression work. The extensive heat exchanger network required to achieve system-wide water and energy balance is not shown in Figure 1.

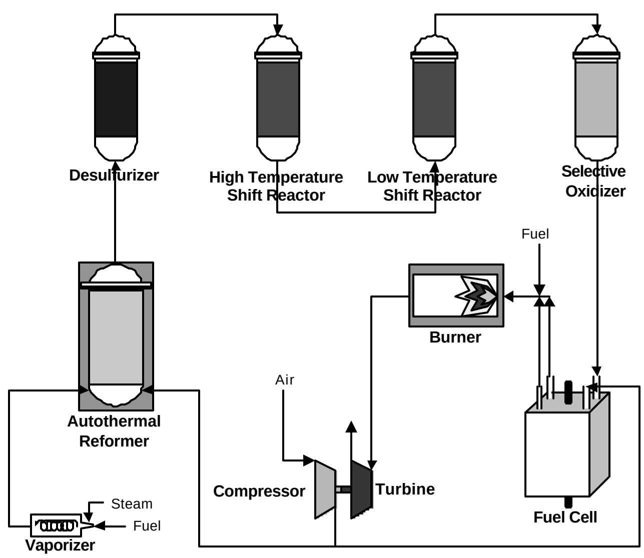

Figure 1. Simplified Process Diagram for the Baseline 2.5 MW Ship Service Fuel Cell Generator.

System physical layout began with the development of a system piping and instrumentation diagram. The component sizing information from the trade-off analyses was used to assemble a three dimensional representation of the system. The layout considered grouping of hot components, minimization of piping runs, and accessibility to equipment for maintenance. The layout, with structural components removed for clarity, is shown in Figure 2.

[1] International Fuel Cells; Fuel Cell Technology for Prototype Logistic Fuel Mobile Systems, Final Report; FCR 14968A; 10/98.

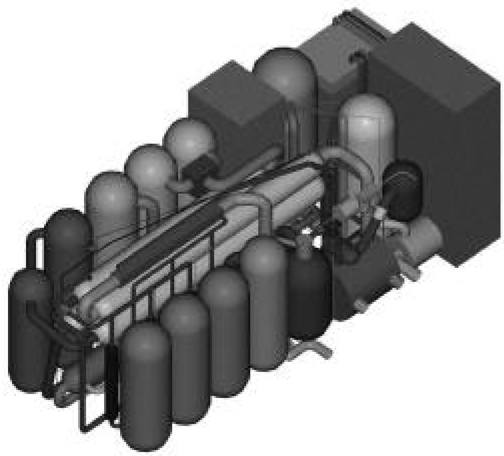

Figure 2. Physical Layout of Baseline 2.5 MW Ship Service Fuel Cell Generator Conceptual Design

The SSFC conceptual design achieves all of the stated design objectives. Further work is required to ensure that the design can meet all of the Navy's requirements in all system operating modes.

A major portion of Phase 1 of the SSFC program focused on demonstrating the suitability of PEM fuel cells for marine application. The focus of this effort was four-fold: assess the effect of salt air on PEM fuel cell operation; qualify the PEM fuel cell to U.S. military shock and vibration standards (MIL-S-901, Grade A and MIL-STD-167-1); characterize the fuel cell stack performance with simulated diesel reformate; and quantify the effect of ammonia and amines (potential contaminants from the fuel processor) on fuel cell performance. Results from the salt air and shock and vibration tests are reported here.

Figure 3 shows a summary of the 50-ppm salt air trial conducted by Ballard Power Systems using a 10-cell PEM fuel cell stack. The plot shows four polarization curves from a single stack operated with different air inlet conditions. Stack performance with ambient air, prior to salt injection is shown ("No Salt"). Polarization data taken at the start of a test run with 50-ppm salt in the inlet air stream is also shown and is almost indistinguishable from the "No Salt" line. It is evident that there is no immediate loss of power due to the introduction of salt at this highest level.

The stack was operated for over ten hours under the 50-ppm salt air condition. Polarization performance was once again recorded after completing ten hours of operation. Even after ten hours of continuous operation under these conditions, the stack does not show any consistent drop in performance. After stopping salt introduction, stack polarization performance was again recorded. This data showed an insignificant difference in the stack power output before the 50-ppm salt air trial and after.

Short term fuel cell stack testing under simulated marine air conditions has not revealed any adverse effects of salt-laden air on fuel cell performance. This result holds even for extremely high levels of salt seen in rough sea states with no other means of protection against salt contamination (i.e. salt filters or louvers). Additional long term salt air testing is planned for late 1999 to assess lifetime effects.

The shock and vibration testing was performed at the National Engineering and Test Establishment in Montreal, Canada. The fuel cell stack tested showed no performance degradation in the shock (MIL-S-901D) and vibration (MIL-STD-167-1) environments. PEM fuel cell technology is thus qualified for marine service as both critical and ancillary equipment either with or without shock mitigation (i.e. dampeners) in place.

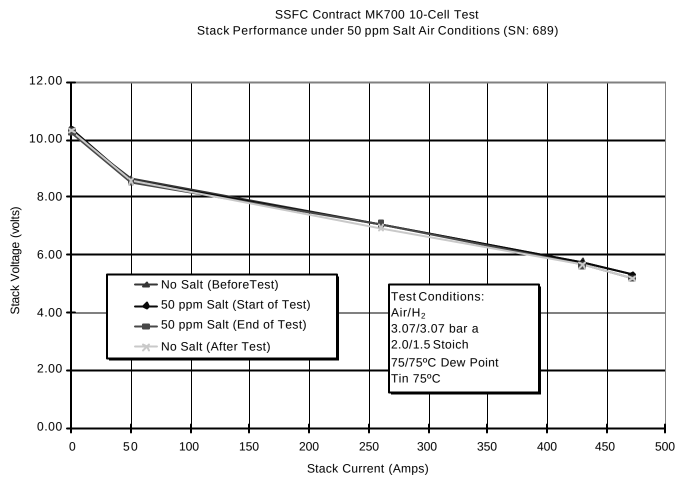

Figure 3 PEM Fuel Cell Response to Salt Air Conditions

The successful fuel cell demonstrations under salt-air, shock and vibration conditions prove the suitability of PEM fuel cells in these naval marine environments. The test conditions were more severe than any expected shipboard conditions. PEM fuel cells should, therefore, be applicable to a variety of shipboard applications.

The SSFC generator fuel processor converts naval distillate fuel (NATO F-76) to a gas acceptable for use by the PEM fuel cell stack. During Phase 1, the critical components of the fuel processor, including the reformer and regenerable desulfurizer, were demonstrated. A 20 kW Phase 1 demonstration scale was chosen to allow economical verification of the technology while providing reasonable scale-up to a 500 kW subsystem during Phase 2. The demonstration fuel processor included an air heater, catalytic autothermal reformer, desulfurizer and carbon monoxide clean up. A photo of the fuel processor test facility at the McDermott Technology, Inc. - Alliance (Ohio) Research Center is shown in Figure 4. The gas clean-up components were sized for a 10-kWe gas capacity to support parametric testing of catalyst breakthrough and to evaluate space velocity design considerations.

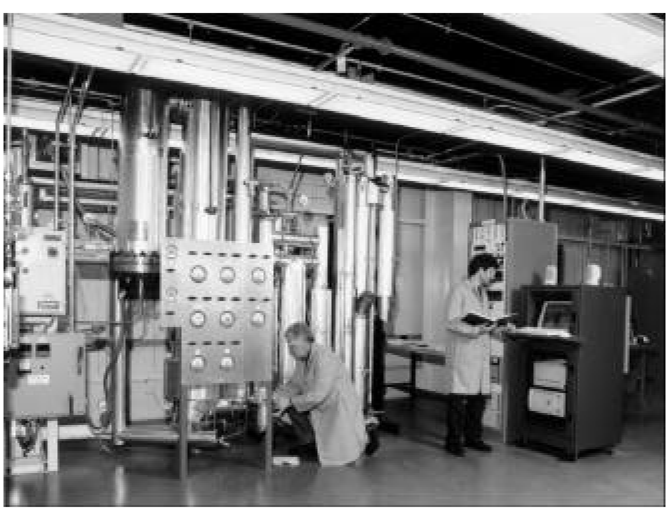

Figure 4. SSFC Fuel Processor Test Facility at McDermott Technology, Inc. - Alliance (OH) Research Center

The SSFC fuel processor test matrix included tests designed to prove the capabilities of the reformer and the desulfurizer. Testing started with operating conditions for which there was previous data. Following these verification tests, operating conditions typical for the SSFC conceptual design as well as conditions intended to define the operability limits of the reformer were evaluated.

Results from testing of the autothermal reformer are shown in Figure 5. The plot shows cold gas efficiency[2] as a function of operating pressure. Test data includes operation at fuel flow rates of 5 and 10 lbm/hr, steam-to-carbon molar ratio of 3.5, and fuel equivalence ratio[3] of 4.2. Reformer efficiency exceeded the target level of 95% for all test conditions. Efficiency calculations result in values greater than 100 percent since they exclude incoming thermal energy in the preheated air and steam (which is converted to chemical energy in the exiting reformate gas). Another important measure of reformer performance is the percent conversion of F-76 fuel to light gases (CH_4, CO_2, and CO). Reformate gas analysis showed that nearly 100 percent of the F-76 fuel was successfully converted to these light gases.

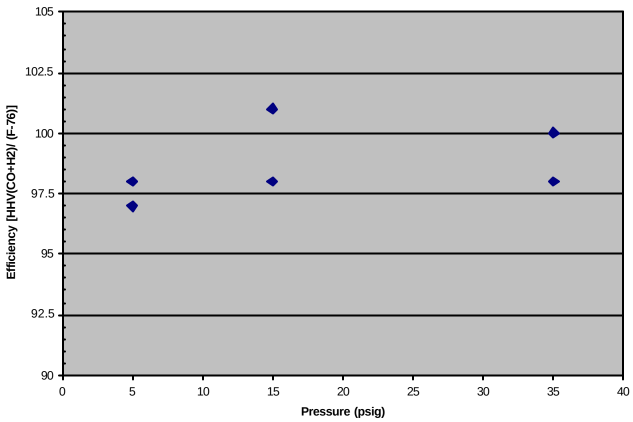

Figure 5. SSFC Fuel Processor Autothermal Reformer Efficiency.

The results described here from the Ship Service Fuel Cell Phase 1 Concept Design and Critical Technology Evaluation confirm the *potential* suitability of a PEM fuel cell-based electrical generator for use in Navy shipboard applications. The system conceptual design presents a compact, efficient generator with high reliability and acceptable cost. The reduced scale demonstrations of critical fuel cell and fuel processor components were successfully completed.

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[2] Cold Gas Efficiency = Higher Heating Value [(H2 + CO)] / [NATO F-76 fuel]
[3] Fuel Equivalence Ratio = Actual Air-to-fuel ratio / Stoichiometric Air-to-fuel ratio